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AN ASSESSMENT OF “PRODUCTIVE” COMPUTATIONAL FLUID DYNAMICS FOR AERODYNAMIC DESIGN

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13. ABSTRACT (<i>Maximum 200 Words</i>) The U.S. Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) has been applying a Government-developed, productivity-oriented, Computational Fluid Dynamics (CFD) methodology to the aerodynamic design of Army missiles. This methodology, dubbed Euler Tunnel Analysis (ETA), uses a robust Euler solver and automated grid generation software to drastically reduce the time required to set up and execute flowfield computations. ETA is described and applied to two hypervelocity missile configurations; one using a bent nose for aerodynamic control and the other using traditional canards. Comparisons are made with wind tunnel data to assess ETA's ability to produce meaningful results for use by aerodynamic designers.				
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I. INTRODUCTION

The aerodynamic design of missiles requires the use of several types of prediction tools. During the preliminary design phase, trade studies are conducted and initial configurations are established. For these applications, quick responding, semi-empirical methods such as Missile DATCOM [1], AP02 [2], and Missile3 [3] have proved to be quite useful. This is because they can provide aerodynamic characteristics for numerous airframe configurations at a multitude of flight conditions, all within a few minutes. However, during the intermediate design phase, it is typical to need a higher degree of modeling fidelity than these tools can provide.

As discussed in Reference 4, higher fidelity approaches range from piecemeal solutions (such as S/HABP [5]) and panel methods (such as CMARC [6] and PANAIR [7]) to marching techniques (like ZEUS [8] and parabolized Navier-Stokes codes) and full-field, elliptical, Computational Fluid Dynamics (CFD) codes (typified by potential flow, Euler, and Navier-Stokes solvers). Each of these kinds of tools has certain predictive strengths and weaknesses as noted in the reference. Each of these approaches was also noted to have weaknesses in terms of practical utility to the aerodynamic designer.

In particular, full-field, elliptical CFD methods were observed to need substantial amounts of time to setup and use. They were also discerned to require in-depth, specialized knowledge in grid generation and solver specifics for their proper utilization. The other kinds of tools were perceived to be limited to specific flight regimes, requiring a piecemeal approach to construct a complete aerodynamic characterization. While all these approaches have their value, there is clearly a need for a contiguous, generally capable, high fidelity, responsive, intermediate level aerodynamic design tool.

To address this need within the AMRDEC, use is being made of a suite of specialized tools assembled within a single framework and given the name Euler Tunnel Analysis (ETA). The features of this tool, its application to the design of a hypervelocity missile, and comparisons of its predictions with wind tunnel measurements will be described in the following sections of this paper.

II. METHODOLOGY

A. Description

ETA is a suite of Government-owned, productivity-oriented, CFD software developed to facilitate aerodynamic design and analysis. It contains a geometry generation code, named CFDGEN, to construct configurations from a library of pre-existing models and model parts. CFDGEN does not require Computer Aided Design / Computer Aided Manufacturing (CAD/CAM) expertise so the aerodynamic designer can use it to construct body geometries without specialized training. Although straightforward to use, CFDGEN is not visually interactive and thereby a bit cumbersome to use. To circumvent this inconvenience, the AMRDEC utilizes some of the less expensive commercial CAD/CAM packages to construct, convert, and repair configurations of interest.

Grid generation is performed in an automated fashion with the NASA/Ames Cart3D [9] methodology developed by Aftosmis, Melton, and Berger. This technique produces an unstructured, Cartesian field grid around the body with relatively few user inputs. The time required to do so has been less than an hour for most of the AMRDEC's cases to date. This attribute saves countless man-hours in problem setup time and greatly enhances productivity. Cart3D, itself a suite of tools, imports geometries using conversion programs and scripts that enable it to accept files in various unstructured and structured formats. The NASA Langley Wireframe Geometry Standard (LaWGS) format (produced by CFDGEN) and the stereolithography solid model format (produced by many CAD/CAM packages) are the ones most often used by the AMRDEC.

The flow solver component of ETA is the TIGER [10] code (originally developed by Melton and modified by Robinson [11]). It is an explicit, unstructured, finite-volume, Euler CFD method that employs Jameson's [12] Runge-Kutta scheme for time integration. The enhancements made by Robinson extend the code by: (1) permitting use of an algebraic enthalpy equation in lieu of the differential energy equation, (2) generalizing the Runge-Kutta integration scheme from its original four-stages to m-stages specified by the user, (3) enhancing robustness near corners and other high-gradient regions at high Mach numbers, and (4) adding the vorticity confinement technique [13] to conserve vorticity in the field and over solid bodies. These modifications reduce computation time, increase TIGER's reliability, and thereby enable the aerodynamicist to be more productive.

Although the geometry, automated grid generation, and solver components of ETA each increase productivity, the primary mechanisms that make this CFD technology useable in the fast-paced aerodynamic design environment are its Graphical User Interface (GUI) and software scripts. These components allow the aerodynamicist to: (1) edit the baseline geometry and create configurations with desired control deflections, (2) establish a directory structure and flow solver input files (based on Mach number, roll angle, and angle of attack), (3) submit each case to the computational platform (either local or remote), (4) check the run status of each case, (5) retrieve the results from the computational platform, and (6) compute aerodynamic coefficients from the flowfield solution for each point of interest. At the AMRDEC, this high

degree of automation has increased the usefulness of CFD to the point of practical, productive application in aerodynamic design.

B. Application

ETA was applied to the aerodynamic design of the two eight-finned, hypervelocity missile configurations shown in Figures 1 and 2. The first of these uses a bent nose to effect aerodynamic control while the second is equipped with conventional canards. Geometries for each airframe were converted from AutoCAD three-dimensional drawings (used to fabricate the wind tunnel models) into stereolithography solid model files. The Cart3D conversion tools were then exercised in command line mode to import them into ETA. A single model was sufficient to derive all configurations of the canard-controlled airframe (based on the undeflected case), but individual representations were required to create each deflection angle for the bent nose configuration.

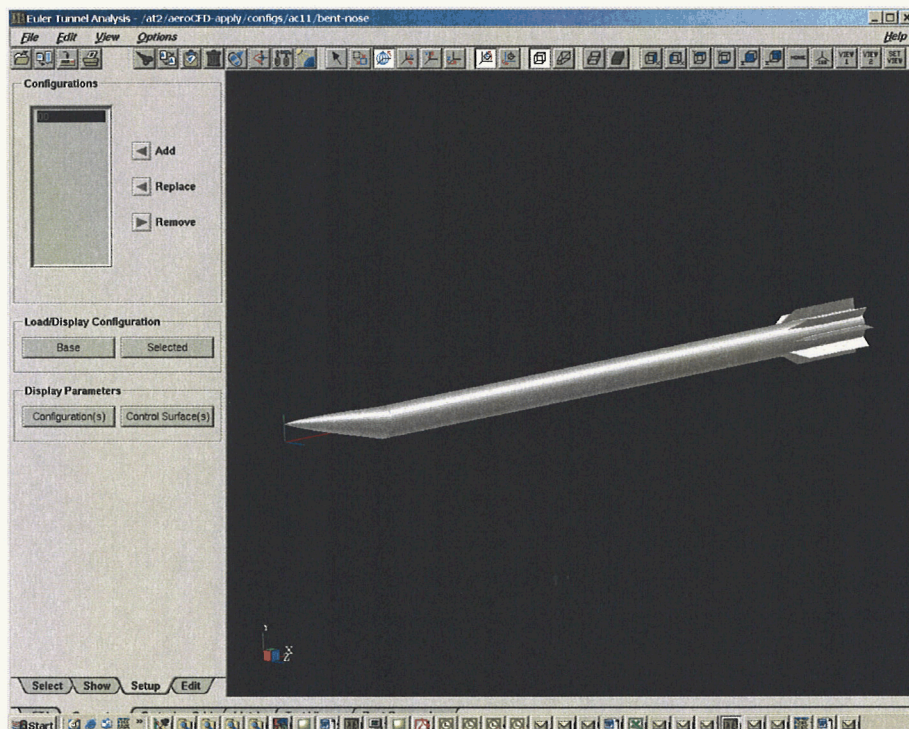


Figure 1. Three-Dimensional Model of Bent-Nose Configuration – Nose Deflected 8 Degrees

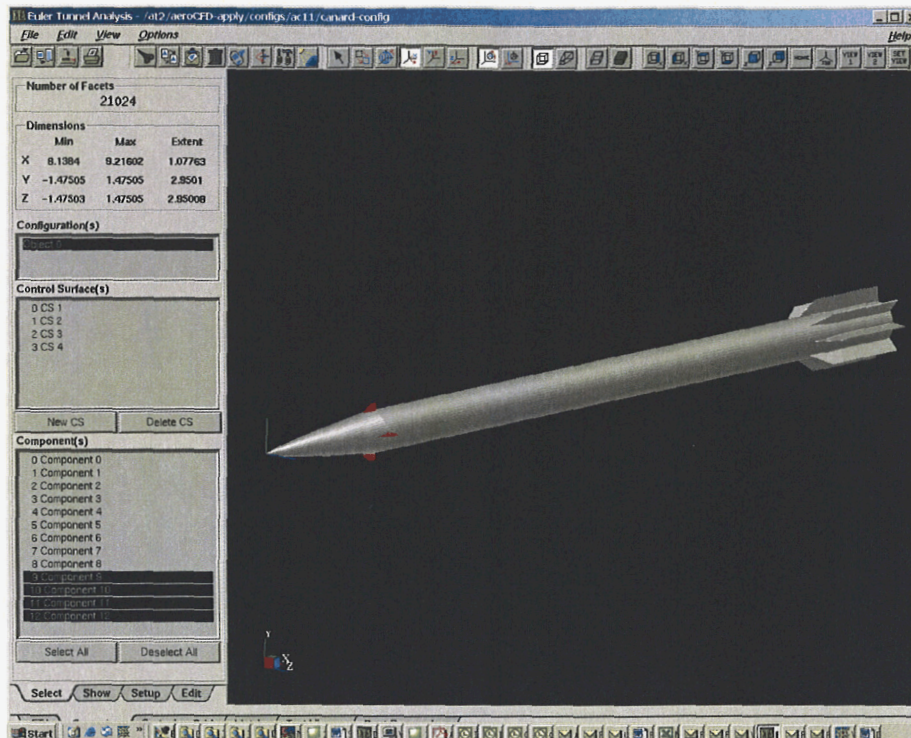


Figure 2. Three-Dimensional Model of Canard-Controlled Configuration

The ETA GUI (Fig. 3) was used to invoke the Cart3D grid generation code (named cubes) and to exercise the cart2tiger program that converts the grid into a TIGER-compatible format. This (and all subsequent processing) was performed in a straightforward, intuitive, point-and-click fashion.

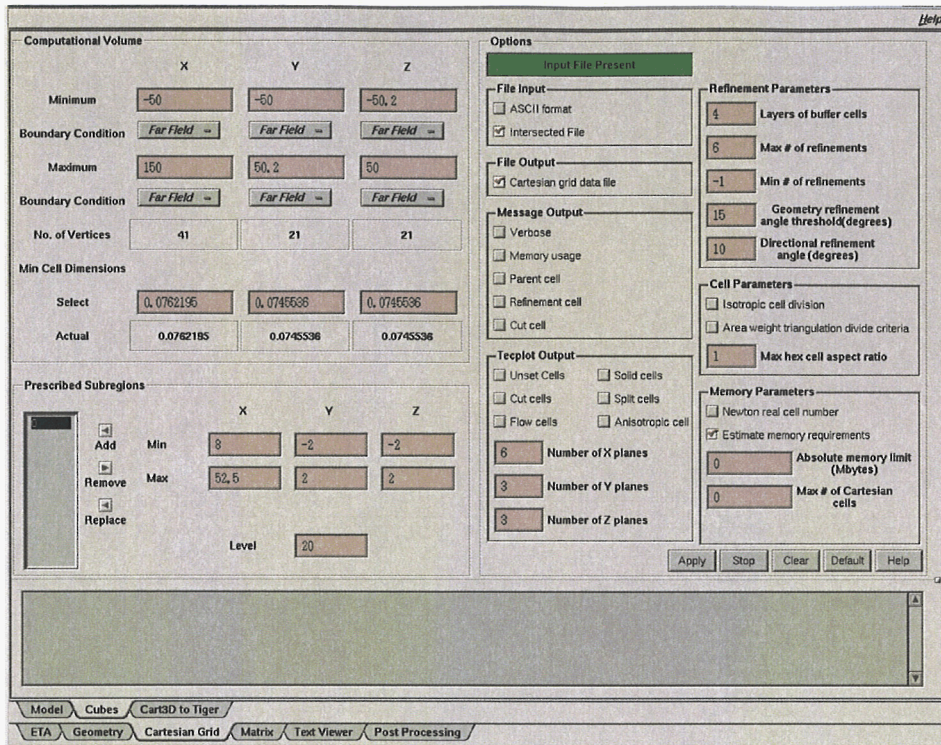


Figure 3. ETA GUI – Cartesian Grid, Cubes Tab

For each bent-nose model, the input to cubes was set to create a field grid with the downstream boundary approximately two body lengths away from the missile. All other boundaries were located approximately one body length away (Fig. 4). The flow conditions were set to freestream values on each boundary, while the minimum grid cell dimensions were set to approximately one one-thousandth (1/1000) of the body length. Six levels of refinement were also specified. These parameters produced grids with approximately one million (1,000,000) Cartesian cells.

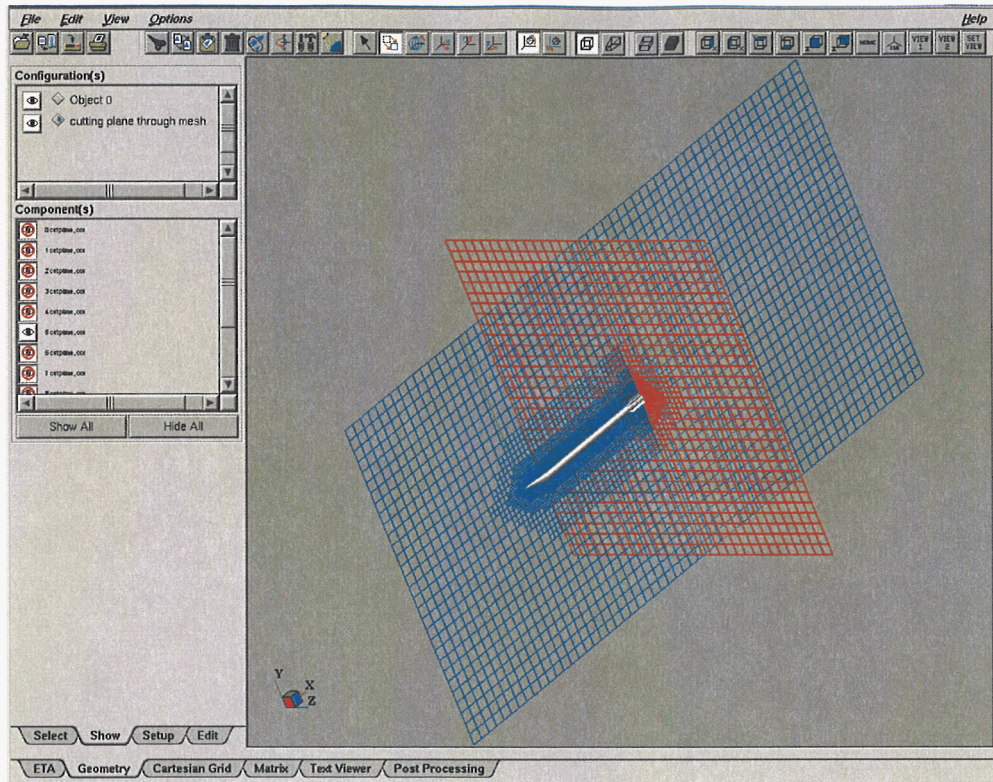


Figure 4. Cart3D Field Grid for 8 Degree Bent-Nose Configuration

For the canard-controlled missile, two types of grids were constructed in a similar fashion: a medium resolution grid and a high resolution grid. This was done to assess the effects of grid resolution. Since the canard vortices were expected to interact with the tail fins, it was important to maintain the highest level of cell refinement in the volume between the canards and tail fins. The ability of cubes to specify regions of constant refinement enabled this to happen. For the medium resolution grid, shown in Figure 5, a minimum cell size of one-fifth ($1/5$) of the canard's exposed semi-span was specified. The high resolution grid used a minimum dimension of one-eleventh ($1/11$) of the semi-span in the lateral and vertical directions and a length of one one-thousandth ($1/1000$) along the missile axis. The corresponding cell count was about 2.8 million and 5.1 million, respectively, for the two types of grids.

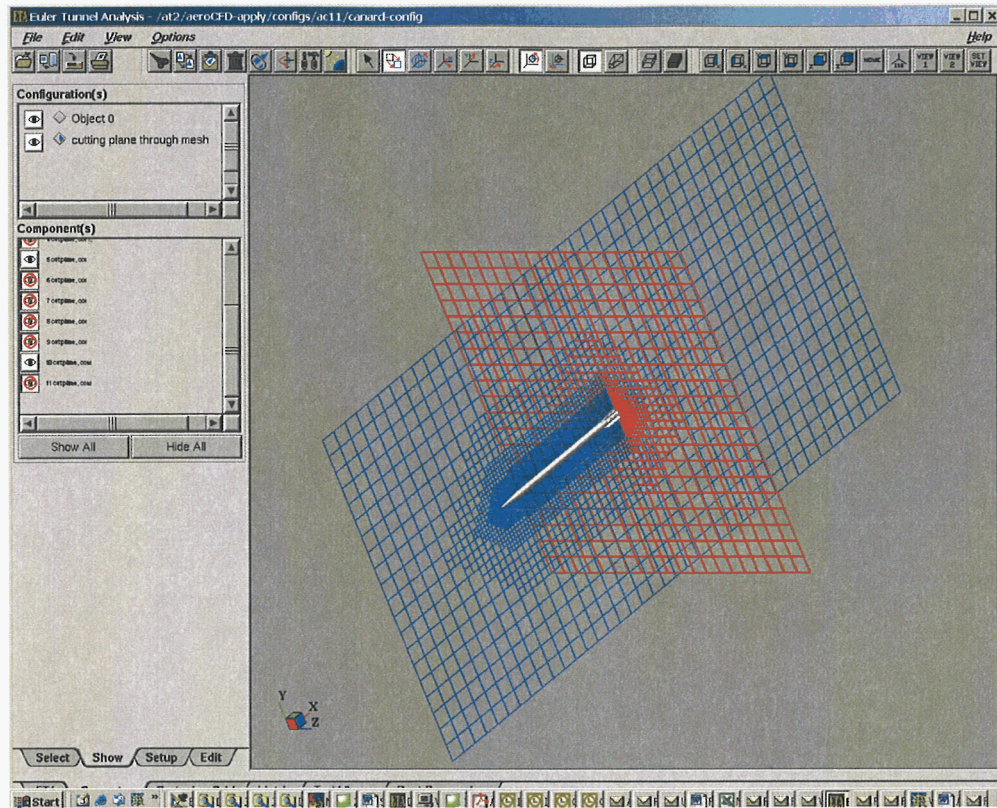


Figure 5. Cart3D Field Grid for Canard-Controlled Configuration

Upon completion of the grid generation (which took less than one hour for each case), the ETA GUI and scripts were used to (1) specify the Mach number, roll angle, and angle of attack combinations to be computed, (2) select the TIGER input parameters, (3) create the required directory structure on the local workstation (a Silicon Graphics O200), (4) transfer the required geometry and input files to the remote supercomputer (a Cray SV-1), (5) submit runs for each case, (6) check the status of each run, (7) download the results of each computation, (8) compute the aerodynamic coefficients for each case, and (9) create ASCII plot files for each angle of attack sweep.

For the bent-nose missile, flowfields and aerodynamic coefficients were computed for a Mach number of 3.0; roll angles of 0, 45, and 90 degrees; and angles of attack from -10 to $+10$ degrees. Computations for the canard-controlled missile were made at Mach numbers 3.0 and 4.5; a roll angle of 0 degrees; and angles of attack from -10 to $+10$ degrees. Canard deflections ranged from 0-degrees to 10-degrees in pitch.

III. RESULTS AND DISCUSSION

Results for the bent-nose configuration are presented in the body-fixed reference frame and compared with wind tunnel data [14] from Figures 6 through 9. These ETA predictions were performed “blind” without examining any of the measurements. It is evident from Figures 6 and 7 that the ETA values for normal force and pitching moment agree quite well with the data for each of the bent-nose deflections. In particular, the pitching moment agrees very well especially since it is referenced to the center-of-gravity (a position that amplifies prediction discrepancies). It should also be noted in Figure 7 that the Euler predictions of ETA begin to deviate from the measurements when the sum of the angle of the nose deflection and the angle of attack begins to exceed 10-degrees. This behavior is expected since viscous forces are likely to affect leeward flow separation on the nose above moderate angles of incidence.

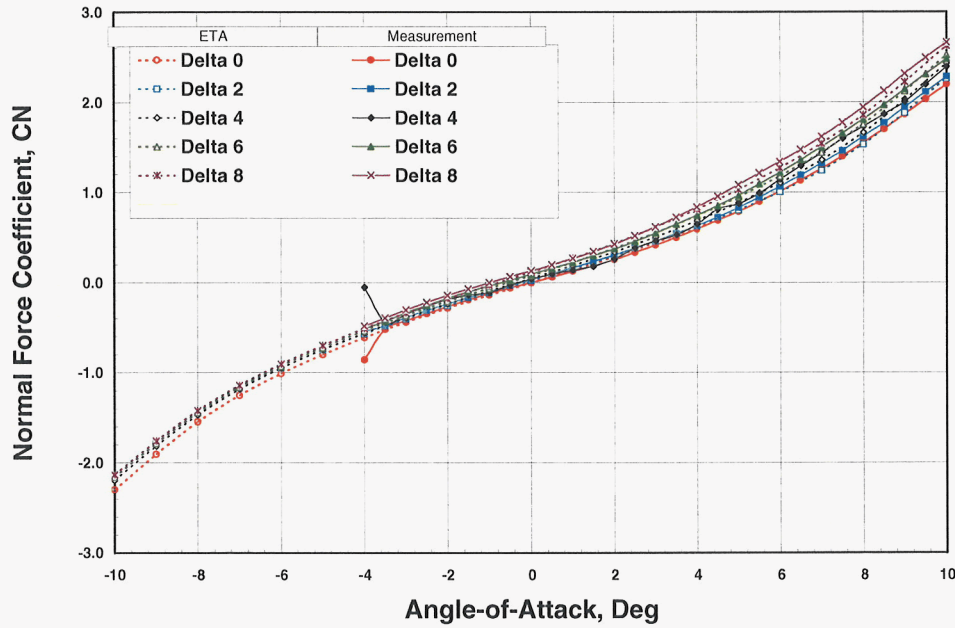


Figure 6. Normal Force Coefficient Versus Angle of Attack for All Bent-Nose Configurations

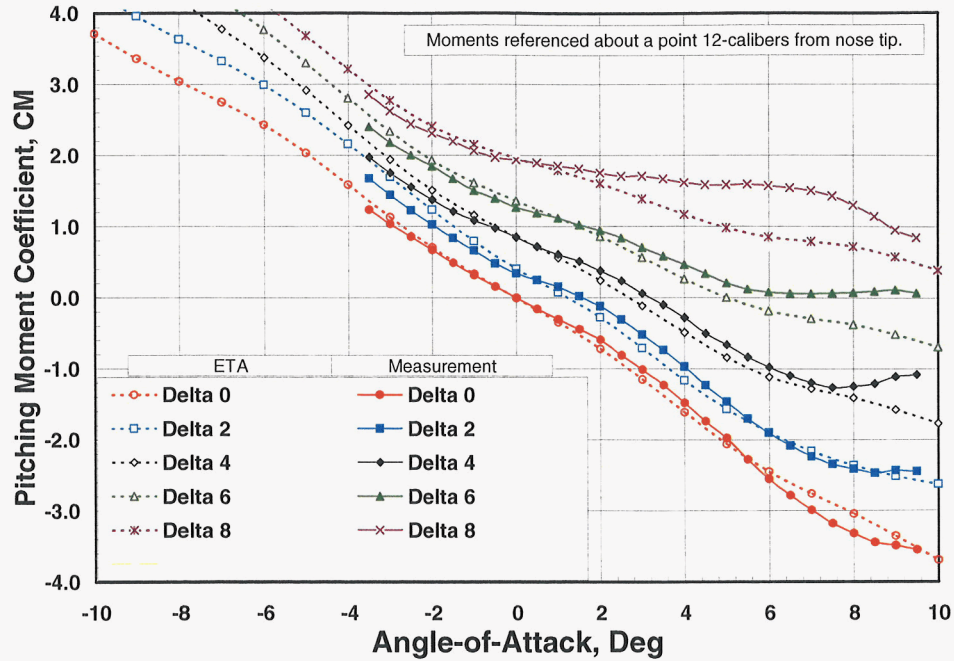


Figure 7. Pitching Moment Coefficient Versus Angle of Attack for All Bent-Nose Configurations

The ability of the ETA methodology to use the same solution grid to address missiles flying in a rolled attitude is shown in Figures 8 and 9. For these 45- and 90-degree roll attitudes, the normal force and pitching moment curves were nearly coincident with measurements; they were not presented to save space. Rather, the more demanding comparison of yawing moment is provided in these two plots. It can be seen that the agreement with measurement is again quite good up to about 4 degrees angle of attack, above which it is expected that viscous forces affect the leeward flow as mentioned before.

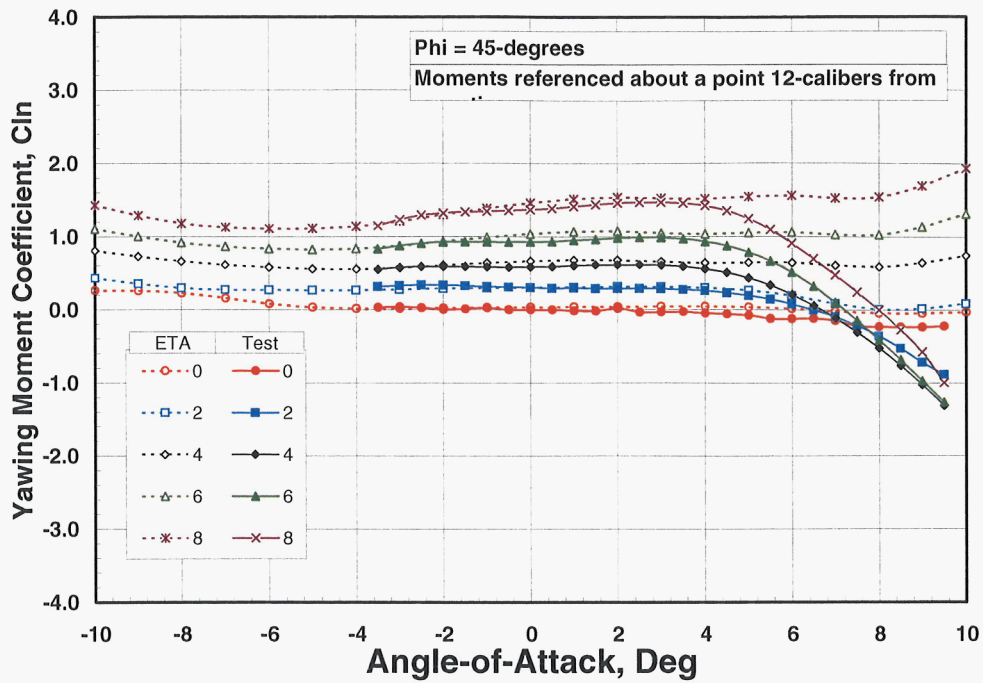


Figure 8. Yawing Moment Coefficient Versus Angle of Attack for All Bent-Nose Configurations at 45-Degrees Roll

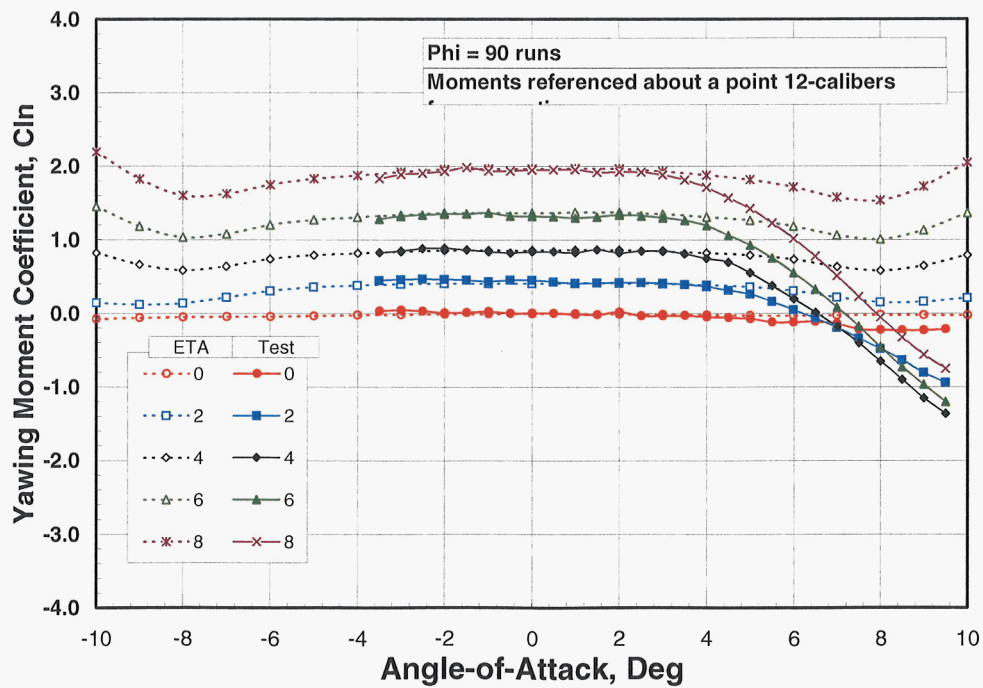


Figure 9. Yawing Moment Coefficient Versus Angle of Attack for All Bent-Nose Configurations at 90-Degrees Roll

For the canard-controlled missile, results for undeflected canards are shown in Figures 10 through 12. Here computations were made with and without surface vorticity confinement on the medium resolution grid. This was done to examine the ability of surface confinement to mimic viscous crossflow separation along long, slender missile bodies. Calculations made on the high resolution grid did not utilize vorticity confinement. It can be seen in Figure 10 that surface confinement improved normal force predictions at the higher angles of attack and that higher grid resolution alone did not do as well. This is shown for Mach 3.0, but it was similarly true for Mach 4.5. Figures 11 and 12, however, show that the high resolution grid without vorticity confinement did a much better job of capturing the pitching moment properties.

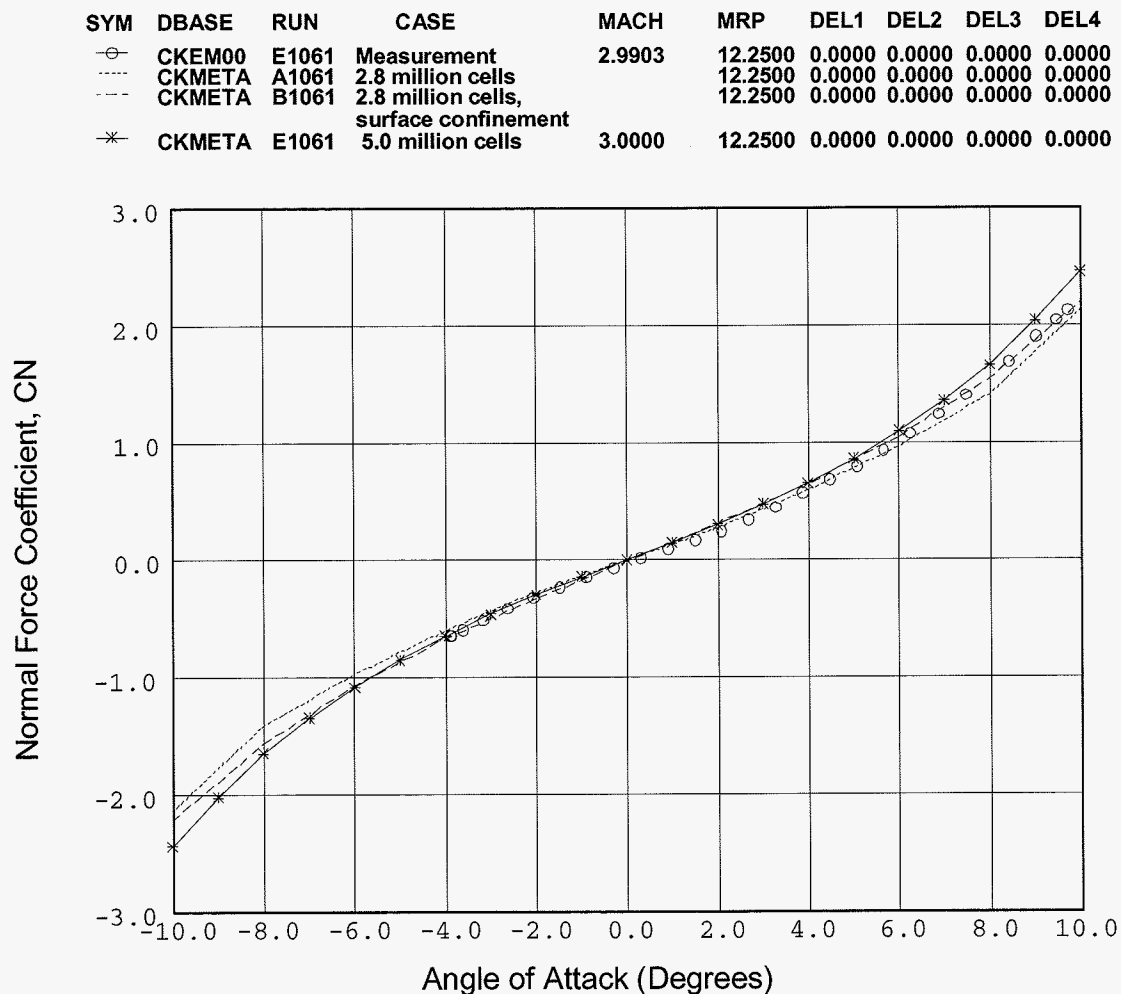


Figure 10. Normal Force Coefficient Versus Angle of Attack for Canard-Controlled Configuration at Mach 3.0

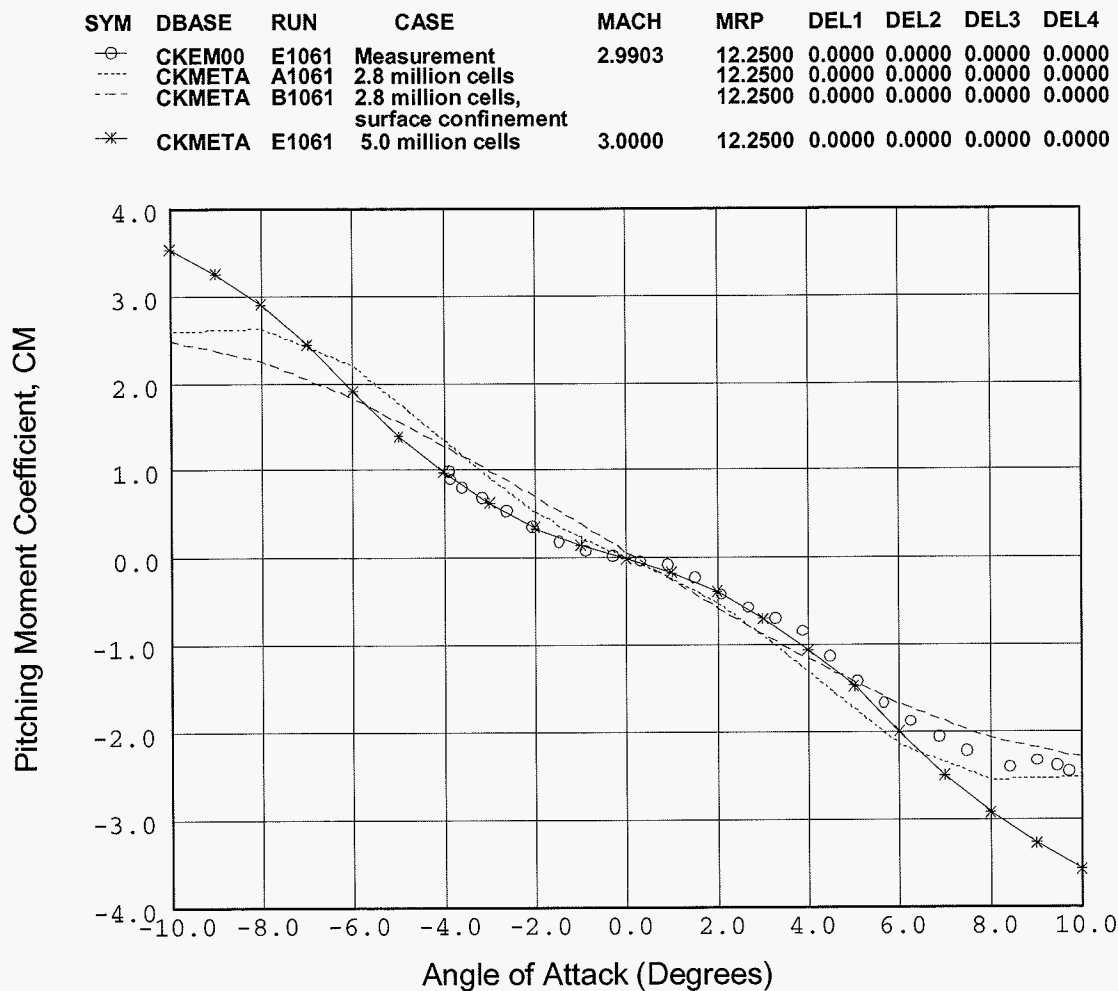


Figure 11. Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 3.0

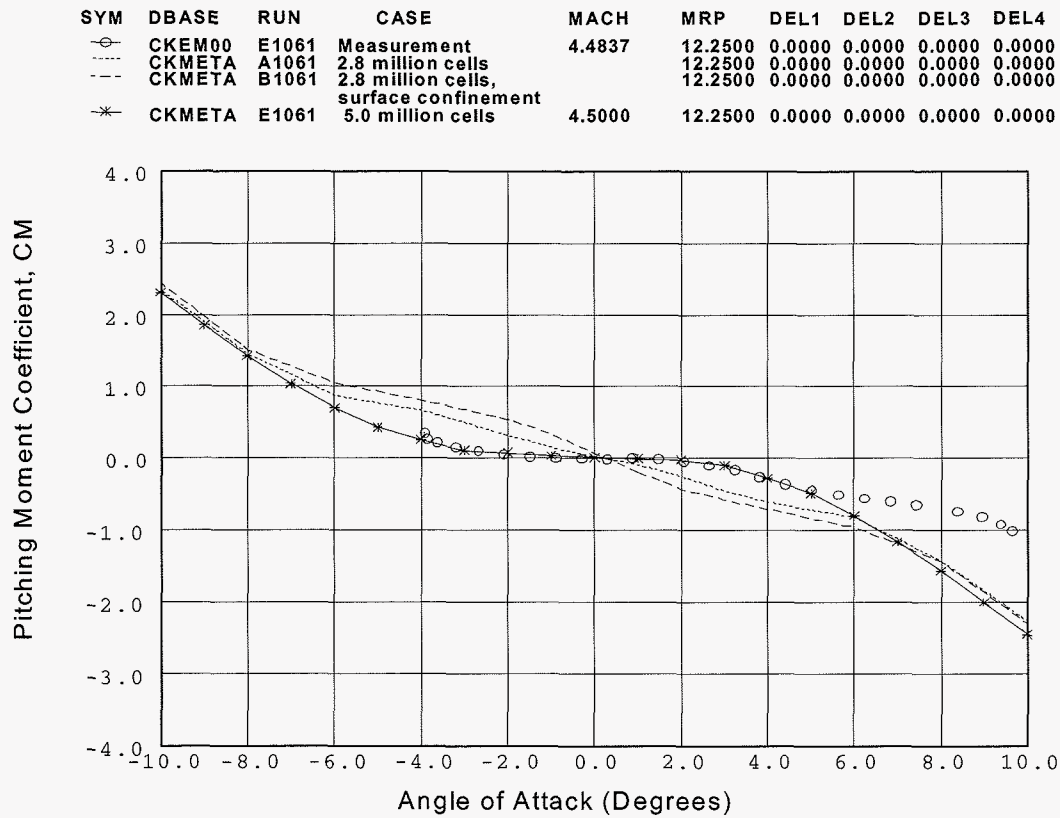


Figure 12. Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 4.5

Comparisons for the deflected canards are provided in Figures 13 and 14. For this configuration, all medium grid computations were made with surface confinement. As before, the high resolution calculations were made without confinement. Although not shown to conserve space, the normal force comparisons are very much like those of Figure 10, showing surface confinement on the medium grid to do better than the high resolution grid alone. The pitching moment comparisons shown in Figures 13 and 14, though, reveal that none of the computations match the data as well as in Figures 11 and 12. While the high resolution results seem to possess some of measurement characteristics from -4 degrees to +4 degrees, the surface confinement results appear to improve agreement above +6 degrees.

SYM	DBASE	RUN	CASE	MACH	MRP	DEL1	DEL2	DEL3	DEL4
○	CKEM00	E1061	Measurement	2.9903	12.2500	0.0000	-10.0000	0.0000	10.0000
---	CKMETA	B1061	2.8 million cells, surface confinement		12.2500	0.0000	-10.0000	0.0000	10.0000
*	CKMETA	E1061	5.0 million cells	3.0000	12.2500	0.0000	-10.0000	0.0000	10.0000

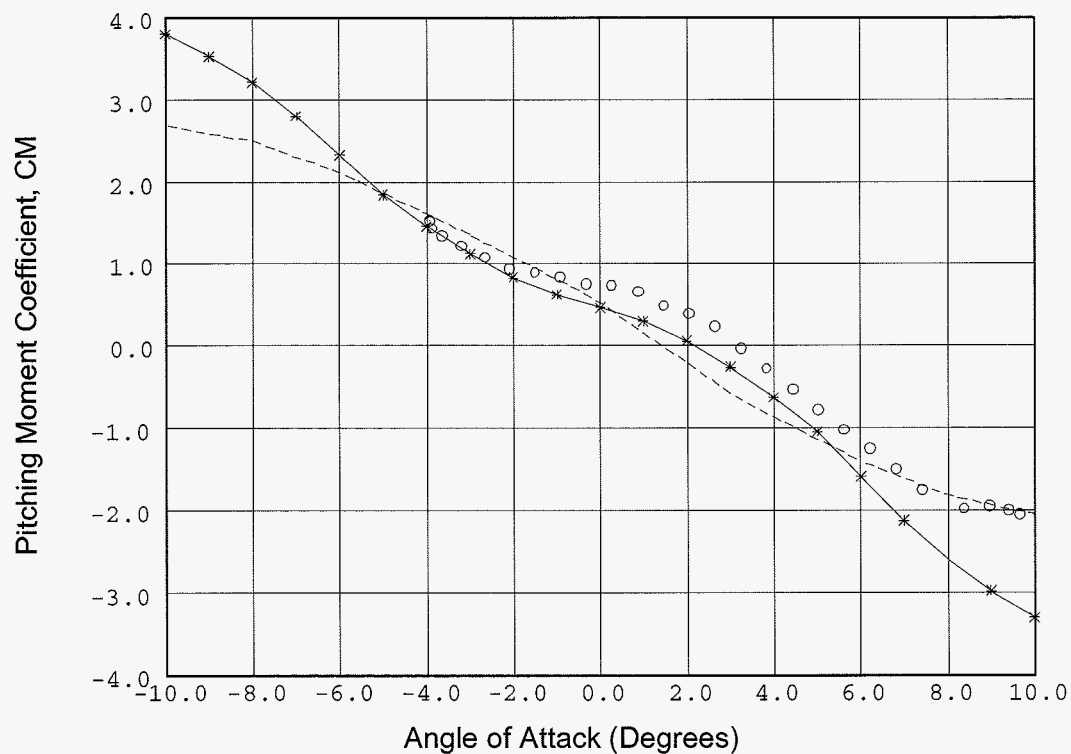


Figure 13. Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 3.0, 10-Degrees Pitch Deflection

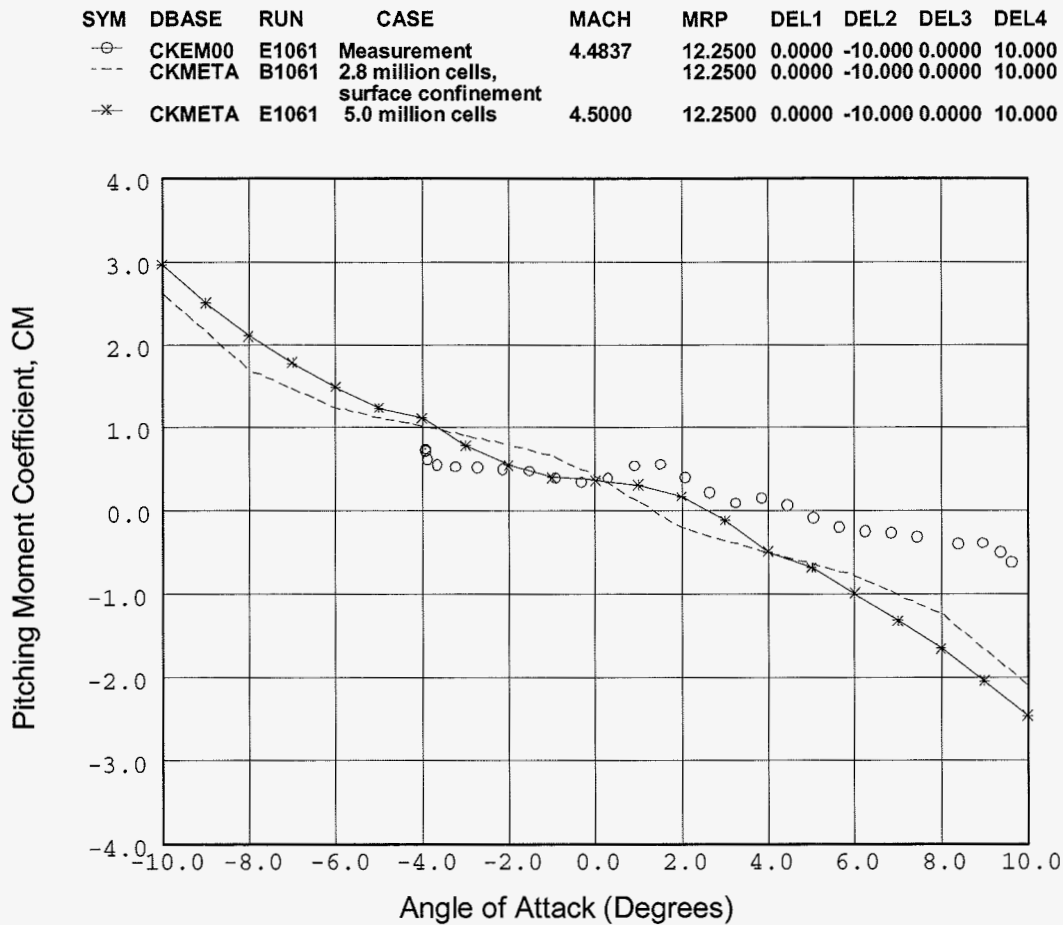


Figure 14. Pitching Moment Coefficients Versus Angle of Attack for Canard-Controlled Configuration at Mach 4.5, 10-Degrees Pitch Deflection

These observations along with those about the undeflected configuration indicate that while the medium resolution grid was adequate to produce accurate values for the normal force coefficient, it was insufficient to properly capture the pitching moment behavior. A high resolution grid was required for this. However, the high resolution grid was unable to produce all the pitching moment properties of the deflected configuration.

With regards to surface vorticity confinement, it is clear that this technique improved the accuracy of normal force calculations on the medium grid, although surface confinement alone was unable to significantly improve the pitching moment results. Nonetheless, comparison of “with and without confinement” curves in Figure 11 suggests that if the confinement corrections were applied to the high resolution grid, the effect would be improved pitching moment accuracy above 6-degrees angle of attack. There appears to be little influence at Mach 4.5 (Fig. 12).

IV. SUMMARY

ETA has shown itself to be a powerful tool in the application of CFD to aerodynamic design. Its use of the Cart3D automated grid generation tool in conjunction with the robust TIGER Euler flow solver make it possible to use CFD in a timely manner. By centralizing user interactions within its GUI and by using scripts to automate many administrative processes, ETA reduces user error and enhances productivity. Further, ETA produces results in a reasonable amount of time. For this study, ETA generated individual alpha sweeps (11 data points for the bent nose, 15 points for the canard missile) overnight when running on a Cray-SV1. Each bent-nose calculation required approximately 8 CPU hours, and each “canard missile” computation ran for around 24 CPU hours.

Comparisons of ETA predictions with wind tunnel data have demonstrated its ability to properly characterize aerodynamic properties of both the bent nose and undeflected canard missile configurations. It must be stated, however, that an appropriate grid is required, and that while vorticity confinement may improve solution accuracy, it cannot compensate for an inadequate grid. With regards to the deflected canard case, further investigation is required to determine suitable input parameters. Further study is also needed to more fully understand the correct application of vorticity confinement.

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